Variability of Measures of Exposure to Environmental Tobacco Smoke in the Home[1-4]

DAVID B. COULTAS,[5] JONATHAN M. SAMET, JOHN F. MCCARTHY, and JOHN D. SPENGLER

SUMMARY: We assessed the variability of four markers of environmental tobacco smoke exposure in 10 homes with 20 nonsmoking and 11 smoking household members. We obtained exposure questionnaires, saliva and urine for cotinine, and air particle samples for respirable particles and nicotine on 10 sampling days: every other day over 10 days, and then 1 day every other week over 10 wk. The mean concentrations of respirable particles in the 10 homes ranged from 32.4 to 78.9 μg/m³, and concentrations of nicotine ranged from 0.6 to 6.9 μg/m³. Linear regression models that included indicator variables for self-reported exposure explained 9 and 6% of the variability of the respirable particle and the nicotine concentrations, respectively. The individual mean urinary cotinine levels standardized to creatinine concentration ranged from 3.9 to 55.8 ng/mg Cr, and for salivary cotinine the mean levels ranged from 0.9 to 4.3 ng/ml. Indicator variables for self-reported exposure explained 8 and 23% of the variability of the urinary and salivary cotinine levels, respectively. We conclude that because of the marked variability of these measures, multiple measurements are needed to establish a stable profile of exposure to environmental tobacco smoke in the home.

AM REV RESPIR DIS 1990; 142:602-606

Introduction

Numerous epidemiologic investigations have examined the adverse effects of passive smoking on children and adults; the evidence is sufficiently compelling to establish passive smoking as a cause of disease in nonsmokers (1, 2). Both the 1986 Surgeon General's Report (1) and the National Research Council (2) have concluded that passive smoking causes increased lower respiratory illness in infants, increased respiratory symptoms in children, reduced lung growth during childhood, and lung cancer in nonsmokers. Although health effects of passive smoking have been convincingly demonstrated, additional research is needed to address unresolved issues concerning this preventable exposure. For example, more precise description of exposure-response relations should be achieved for the already established health effects. Uncertainties concerning the adverse effects of passive smoking in the workplace and on the occurrence of ischemic heart disease must also be resolved.

The conduct of this research would be facilitated by improved methods for exposure assessment. In most epidemiologic studies on passive smoking published to date, exposure to environmental tobacco smoke, the combination of exhaled mainstream smoke and sidestream smoke, has been assessed by questionnaire. However, exposure to environmental tobacco smoke can also be estimated with air monitoring and measurement of biologic markers in body fluids, such as salivary cotinine. Biologic markers are increasingly emphasized as a standard for validating questionnaire responses. To characterize the relationships among these alternative approaches for assessing passive smoking in the home environment, we conducted a prospective study of 10 households. We periodically collected questionnaire information on exposure and measured respirable particles and nicotine in air samples and urinary and salivary cotinine in the 20 nonsmokers in these households.

Methods

Sample Selection

Between February and December 1986, 149 nonsmoking volunteers, 18 years of age and older, were recruited from Albuquerque and surrounding communities to participate in a study of the accuracy of questionnaire assessment of exposure to environmental tobacco smoke (3). From this sample, we selected 10 subjects living with at least one cigarette smoker and requested the participation of the entire household for this investigation. The households were selected on the basis of willingness to participate and location, and were not intended to be representative of the original sample.

Data Collection

Between March and October 1986, we obtained exposure questionnaires, saliva and urine, and air particle samples on 10 sampling days: every other day over 10 days, and then 1 day every other week over 10 wk. The questionnaires and saliva and urine specimens were obtained at the end of a 24-h air monitoring period (described below). From the questionnaires, we determined the reported number of smokers and number of hours that the subjects were exposed during the previous 24 h to cigarettes, cigars, and pipes at home, at work or school, in a vehicle, and in other places. Questionnaires were self-completed by the adults, and by a parent for children 14 years of age and younger. Spot saliva and urine specimens were obtained and frozen at −20° C until the cotinine assays were performed.

Cotinine Assay

Cotinine was quantitated by a double antibody radioimmunoassay, as described by Langone and coworkers (4). A specific antiserum produced in rabbits was supplied by Dr. Helen Van Vunakis (Brandeis University). Urine samples were diluted 1:4 for the assay. The sensitivity of the assay in our hands was 36 pg/tube or 0.78 ng/ml of urine (4,204 pmol/L). Urine creatinine concentrations were determined by the Jaffe reaction (5), and the cotinine concentrations were standardized to the creatinine concentrations. Assays were performed without knowledge of questionnaire responses.

(*Received in original form September 26, 1989 and in revised form February 5, 1990*)

[1] From the New Mexico Tumor Registry, Cancer Center, University of New Mexico Medical Center, Albuquerque, New Mexico, and the Department of Environmental Science Engineering, Harvard School of Public Health, Boston, Massachusetts.

[2] Supported by Grant No. EPA CR811650 from the Environmental Protection Agency.

[3] Presented in part at the Air Pollution Control Association Specialty Conference on Combustion Processes and the Quality of the Indoor Environment, Niagara Falls, New York, September 1988.

[4] Correspondence and requests for reprints should be addressed to David B. Coultas, M.D., New Mexico Tumor Registry, 900 Camino de Salud NE, Albuquerque, NM 87131.

[5] Recipient of an Edward Livingston Trudeau Scholar Award from the American Lung Association.

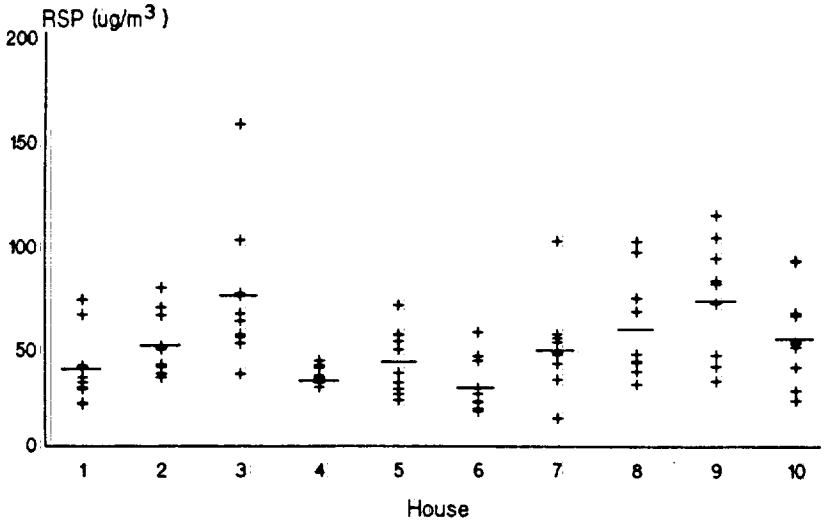

Fig. 1. Respirable particle concentrations (RSP) measured during 24-h sampling periods in 10 homes with at least one cigarette smoker. The bars indicate the mean levels for each home.

Particle Measurements

In the major activity room of each home, Harvard School of Public Health impactors (6), operating at a flow rate of 4 L/min, were used to collect respirable particles and gaseous nicotine samples. Through a timed solenoid switching valve, two impactors used a common, mass-flow controlled pump, and each impactor operated on alternate 15-min collection cycles. Respirable particle samples, 2.5 μm in diameter or less, were collected on Teflon® filters (Membrana, Inc., Pleasanton, CA), and nicotine was collected on sodium-bisulfate-treated glass fiber filters (Millipore Corp., Bedford, MA) to minimize its volatilization. After extraction from the filter, analysis for nicotine was done on a Shimadzu GC7A gas chromatograph (Columbia, MD) with a flame ionization detector. The nicotine collection and extraction procedure is a modification of that described by Hammond and coworkers (7). The recovery of nicotine by this procedure has been shown to be 98% efficient. The sensitivity for detection of respirable particles and nicotine was 5.0 μg and 0.05 ppm, respectively.

Data Analysis

Variability of questionnaire responses, respirable particle and nicotine concentrations, and urinary cotinine levels were assessed with univariate analyses. From the questionnaire responses, we used the total number of household smokers, including cigarette, cigar, and pipe smokers, and the total number of hours exposed as the measures of home exposure. The predominant source of tobacco smoke was from cigarette smoking. During the entire sampling period, there were only 4 days in which any subject reported exposure to a cigar smoker, and none reported exposure to a pipe smoker.

To examine determinants of the variability in the measurements, we used multiple linear regression. The dependent variables (respirable particles, nicotine, urinary cotinine, and salivary cotinine) were analyzed as continuous variables. For the predictive factors, indicator variables were defined for house (HOUSE = 1 to 10), individual (INDIVIDUAL = 1 to 20), age group (AGE GROUP < 18 yr versus ≥ 18 yr), season (SEASON = March–April versus May–October), and number of smokers per day (NUMBER = zero versus ≥ 1). Other independent variables, number of hours (HOURS) exposed per day, respirable particles, and nicotine were continuous.

Data analyses were performed with standard programs of the Statistical Analysis System (8).

Results

The 10 households included 11 cigarette smokers and 20 nonsmokers, 11 females and nine males 1.5 to 74 yr of age. The homes included eight unattached single family houses, one mobile home, and one apartment.

Reports on exposure to tobacco smoke in the home were obtained for all 10 sampling days from 17 subjects, and for 9 days from three subjects. The reported number of cigarette smokers in the home per day did not vary widely. The median number (range) of smokers per day was one for 18 of the nonsmoking subjects (zero to 10), zero for one subject (zero to 1), and four for one subject (2 to 25). Greater variability was reported for the number of hours exposed to cigarette smoke in the home, with the median number of hours ranging from zero to 11 h.

Respirable particle and nicotine concentrations were obtained for 99% of the sampling days (figures 1 and 2). The mean concentrations of respirable particles in the 10 homes ranged from 32.4 μg/m³ (SD = 13.1) to 76.9 μg/m³ (SD = 32.9), and concentrations of nicotine ranged from 0.6 μg/m³ (SD = 0.69) to 6.9 μg/m³ (SD = 8.2). Spearman's correlation coefficient between the respirable particle concentrations and the nicotine concentrations was 0.54 (n = 99, p = 0.0001).

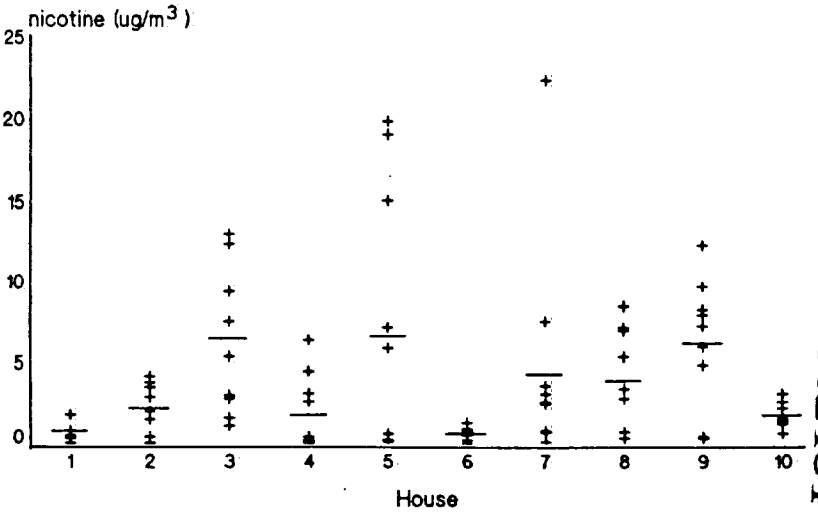

Fig. 2. Atmospheric nicotine concentrations measured during 24-h sampling periods in 10 homes with at least one cigarette smoker. The bars indicate the mean levels for each home. Levels of nicotine were undetectable on 1 or more days in Houses 1 (n = 3), 2 (n = 2), 4 (n = 2), and 8 (n = 1).

TABLE 1

COEFFICIENTS OF DETERMINATION FOR THREE LINEAR REGRESSION MODELS* PREDICTING RESPIRABLE PARTICLE AND NICOTINE CONCENTRATIONS IN AIR SAMPLES FROM 10 HOMES, NEW MEXICO, 1986

	R^2		
Dependent Variable	Model 1	Model 2	Model 3
Respirable particles, μg/m³	0.34	0.08	0.09
Nicotine, μg/m³	0.28	0.04	0.06

* Independent variables: Model 1 = HOUSE (1 to 10, representing the 10 homes); Model 2 = NUMBER (zero versus ≥ 1 smokers) + SEASON (March–April versus May–October); Model 3 = NUMBER (zero versus ≥ 1 smokers) + HOURS (continuous) + SEASON (March–April versus May–October).

TABLE 2

REGRESSION COEFFICIENTS FOR MODEL THREE* PREDICTING RESPIRABLE PARTICLE AND NICOTINE CONCENTRATIONS IN AIR SUPPLY FROM 10 HOMES, NEW MEXICO, 1986

	Regression Coefficients for Model 3		
	One or More Smokers	HOURS	Cold Months
Respirable particles, μg/m³	+17.3 (−3.0, 37.7)†	+0.4 (−1.0, 1.8)	+8.9 (−1.1, 18.9)
Nicotine, μg/m³	+2.1 (−2.7, 5.9)	+0.2 (−0.1, 0.5)	−0.7 (−2.5, 1.1)

* See text and table 1 for description of Model 3.
† 95% confidence intervals shown in parentheses.

The variability of respirable particle and nicotine concentrations for the two sampling periods, every other day or every other week, were described with one-way analysis of variance. For the respirable particle concentrations, the intra-house mean square error, describing the extent of variation for a particular household, was greatest for sampling every other day (516.8) compared with every other week (258.7). A contrasting pattern of variation was observed for nicotine, with mean square errors of 3.6 and 19.0 for every other day and every other week, respectively.

For the particle and nicotine measurements, we used linear regression to examine factors influencing the concentrations and the variability of the concentrations. A model that included variables representing each of the 10 houses explained the greatest amount of variability, as shown by the magnitude of the R^2 value (table 1). Compared with the model with the variables for individual homes, the models that included number of smokers explained markedly lower percentages of the variability of levels of nicotine and particles. Although not statistically significant, increases in respirable particles were associated with exposure to one or more cigarette smokers in the home and with the colder months, March and April (table 2). There was no association of particle levels with the number of hours of exposure. Nicotine levels increased, although not significantly, with exposure to smokers in the home, but were not predicted by the season (table 2).

Cotinine levels were obtained on 187 urine specimens from 20 nonsmokers, and 153 saliva specimens were obtained from 16 nonsmokers. We were unable to obtain saliva specimens from four children, all 4 yr of age or younger. The individual mean urinary cotinine levels standardized to urinary creatinine concentration ranged from 3.9 ng/mg Cr (SD = 6.5) to 55.8 ng/mg Cr (SD = 32.0). For salivary cotinine, the mean levels ranged from 0.9 ng/ml (SD = 0.8) to 4.3 ng/ml (SD = 1.4). The mean urinary cotinine levels and variability tended to be greater in the children than in the adults (figures 3 and 4) (data not shown for salivary cotinine). Spearman's correlation between the urinary cotinine and salivary cotinine concentrations was 0.32 (n = 153, p = 0.0001). Correlations between the cotinine levels and the atmospheric markers were highest for salivary cotinine and nicotine (table 3).

As for the atmospheric markers, we

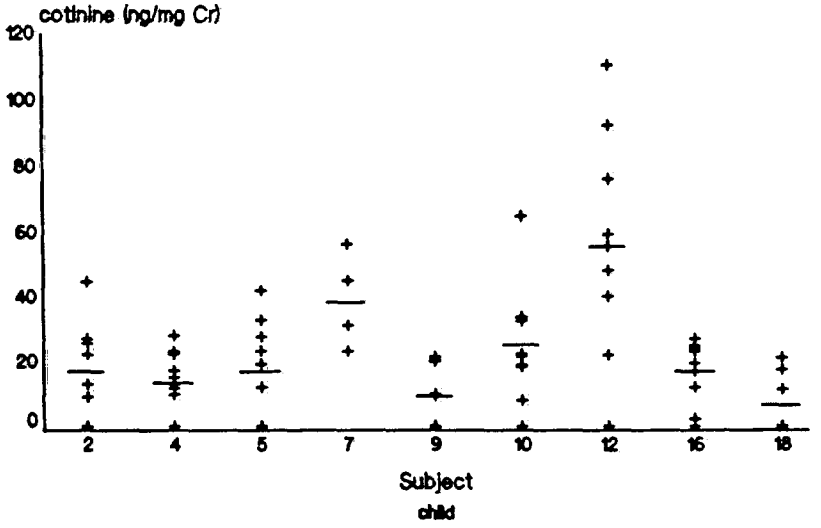

Fig. 3. Urinary cotinine concentrations standardized to urinary creatinine concentration in nine nonsmoking children from homes with at least one cigarette smoker. The bars indicate the mean levels for each child. Levels of urinary cotinine were undetectable on 1 or more days for Subjects 2 (n = 2), 4 (n = 2), 5 (n = 3), 9 (n = 4), 10 (n = 1), 12 (n = 1), 16 (n = 1), and 18 (n = 5).

TABLE 3

SPEARMAN'S CORRELATION COEFFICIENTS BETWEEN COTININE LEVELS IN URINE AND SALIVA AND RESPIRABLE PARTICLES AND NICOTINE, NEW MEXICO, 1986

	r
Urinary cotinine, n = 187	
Respirable particles	0.25
Nicotine	0.15
Salivary cotinine, n = 153	
Respirable particles	0.25
Nicotine	0.38

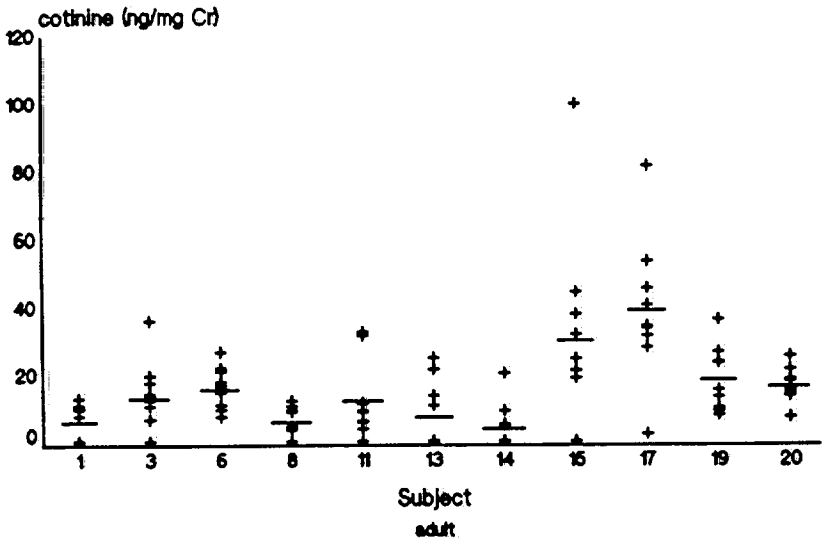

Fig. 4. Urinary cotinine concentrations standardized to urinary creatinine concentration in 11 nonsmoking adults from homes with at least one cigarette smoker. The bars indicate the mean levels for each adult. Levels of urinary cotinine were undetectable on 1 or more days for Subjects 1 (n = 4), 3 (n = 2), 8 (n = 2), 11 (n = 1), 13 (n = 6), 14 (n = 6), and 15 (n = 2).

TABLE 4

COEFFICIENTS OF DETERMINATION FOR THREE LINEAR REGRESSION MODELS* PREDICTING URINARY AND SALIVARY COTININE CONCENTRATIONS IN NONSMOKERS EXPOSED TO TOBACCO SMOKE, NEW MEXICO, 1986

	R^2		
Dependent Variable	Model 1	Model 2	Model 3
Urinary cotinine, ng/mg Cr	0.47	0.05	0.08
Salivary cotinine, ng/ml	0.57	0.09	0.23

* Independent variables: Model 1 = INDIVIDUAL (1 to 20, representing the 20 nonsmoking individuals); Model 2 = NUMBER (zero versus ≥ 1 smokers) + SEASON (March–April versus May–October) + AGE GROUP (< 18 versus ≥ 18 yr); Model 3 = NUMBER (zero versus ≥ 1 smokers) + HOURS (continuous) + SEASON (March–April versus May–October) + AGE GROUP (< 18 versus ≥ 18 yr).

used one-way analysis of variance to describe the variability in urinary and salivary cotinine concentrations during the two sampling periods: every other day or every other week. In contrast to the atmospheric markers, the variability in cotinine levels was comparable for the two periods. The intraindividual mean square errors for urinary cotinine were 175.8 and 194.8, and for salivary cotinine it was 0.9 and 0.7.

For the urinary and salivary cotinine levels, we also examined determinants of variability and concentration with linear regression. Models that included indicator variables for the 20 nonsmoking subjects explained 47 and 57% of the variability in cotinine levels, respectively (table 4). Compared with this model, other models that included exposure to environmental tobacco smoke and age group explained much lower proportions of the variability. Urinary cotinine levels were significantly ($p < 0.05$) higher among children than among adults (table 5). Although the effect was not significant, exposure to one or more smokers resulted in higher urinary cotinine levels than did no exposure. The number of hours of reported exposure and the season were not significant predictors of cotinine level. For salivary cotinine level, the hours of exposure was the only significant predictor.

Prediction of level of urinary or salivary cotinine was not greatly improved with the use of respirable particles or nicotine as independent variables. The proportions of the variability in the urinary cotinine levels explained by respirable particle and nicotine concentrations were 0.03 and 0.04, respectively. For salivary cotinine, the corresponding R^2 values were only slightly higher at 0.07 and 0.13, respectively.

Discussion

Environmental tobacco smoke is a complex mixture of gases and particles that changes as it ages. Personal exposure to environmental tobacco smoke is determined by the nonsmoker's activity pattern; exposure may be received in the diverse microenvironments encountered throughout the course of day-to-day activities. For many nonsmokers, the home is a predominant location of exposure (9). In this investigation, we assessed methods for measuring exposure to environmental tobacco smoke in the home that can be used for epidemiologic research: air monitoring, questionnaires, and biologic markers.

In other populations, cigarette smok-

TABLE 5

REGRESSION COEFFICIENTS FOR MODEL THREE* PREDICTING URINARY AND SALIVARY COTININE CONCENTRATIONS IN NONSMOKERS EXPOSED TO TOBACCO SMOKE, NEW MEXICO, 1986

	Regression Coefficients* Model 3			
	One or More Smokers	HOURS	SEASON	AGE GROUP
Urinary cotinine, ng/mg Cr	+5.4 (−4.8, 15.6)†	+0.8 (0.0, 1.6)	−0.2 (−5.8, 5.4)	+5.4 (0.0, 10.8)
Salivary cotinine, ng/ml	+0.13 (−0.06, 0.86)	+0.15 (0.09, 0.21)	−0.02 (−0.41, 0.37)	−0.81 (−1.34, −0.28)

* See text and table 4 for description of Model 3.
† 95% confidence intervals shown in parentheses.

ing has been shown to be a strong source of respirable particles in the home (1, 10, 11). Spengler and coworkers (10) estimated that the average increase in the indoor concentration of respirable particles was 20 $\mu g/m^3$ for each smoker. We estimated an average increase of 17 $\mu g/m^3$ for one or more smokers (table 2); the average concentrations in the New Mexico homes (figure 1) were above the mean of 24 $\mu g/m^3$ in nonsmoking homes from six U.S. cities (10). Nicotine was present on most sampling days (figure 2). The moderate correlation between the nicotine and respirable particle concentrations (Spearman's $r = 0.54$) confirms the importance of tobacco smoking as a source of particulate pollution in the home. Little data have been reported on nicotine concentrations in the home (1, 2); the levels in the New Mexico homes were somewhat lower than an average concentration of 11.2 $\mu g/m^3$ reported by Muramatsu and coworkers (12) for three homes in Japan. However, the results from our investigation and the Japanese study are not directly comparable because the Japanese data were from personal samples. Furthermore, information on intensity or duration of exposure to tobacco smoke was not provided for the Japanese homes. In a recent study in North Carolina, the homes of 27 children were monitored overnight for nicotine with a sampler that was located near the child (13). The average nicotine concentration in homes with smokers was 3.74 $\mu g/m^3$, with a range from about 1 to 7 $\mu g/m^3$. The higher levels in our study may reflect the differing sampling strategies; the nicotine sampler remained in the activity room throughout the monitoring period in our study, but it was moved to the child's bedroom in the North Carolina study when the child slept.

Questionnaires on exposure to environmental tobacco smoke generally assess the strength of the source, e.g., the number of smokers or the number of cigarettes consumed, and the duration of exposure. The concentration of environmental tobacco smoke, however, depends not only on the source strength but on room size, mixing, adsorption of smoke components, and the rate of exchange of indoor with outdoor air. Personal exposure also varies with the nonsmoker's proximity to the smoker. Questionnaires cannot comprehensively and accurately assess each of these factors.

Not surprisingly, we found that the questionnaire responses were poor predictors of concentrations of respirable particles and nicotine (table 1). The highest R^2 values were obtained with a regression model that included variables for the individual homes; presumably, these variables represented characteristics of the homes, many of them unmeasurable, that determined concentrations at a given level of smoking.

Cotinine, nicotine's major metabolite, has a half-life of 20 to 40 h in nonsmokers (1). It can serve as a specific biologic marker of exposure to environmental tobacco smoke that has been received over a period of days. At any given level of nicotine exposure, cotinine levels in body fluids are also determined by uptake, metabolism, and excretion (1). In regression analyses to predict cotinine concentrations, the models that included variables for the individual subjects gave the highest R^2 values (table 4). Models including only the questionnaire-derived exposure measures or the atmospheric markers had low R^2 values. Our findings in a large population-based survey were similar (14). In 247 nonsmoking adults with a detectable cotinine level, variables for subject age, number of cigarettes smoked by the spouse, and number of cigarettes smoked by other household smokers explained only 2% of the variance of salivary cotinine level for females, and 16% of the variance for males.

In epidemiologic investigations of the adverse health effects of environmental tobacco smoke, questionnaires have been the sole approach for assessing exposure (1, 2). Air monitoring and biologic markers represent promising and feasible approaches for assessing exposure to environmental tobacco smoke. For the home environment, our data demonstrate that indexes of exposure to environmental tobacco smoke based on questionnaires, biologic markers, and air monitoring are not tightly correlated. At a particular level of exposure, as assessed by inventory of household smokers, concentrations of respirable particles and nicotine vary widely, as do levels of salivary and urinary cotinine. The variability of the atmospheric and biologic markers must be considered in using them as standards for assessing misclassification by questionnaires. For environmental tobacco smoke exposure at home, our data suggest that single measurements of either levels of environmental tobacco smoke components or of biologic markers are not adequate for characterizing usual exposure. Multiple measurements are needed. It may be misleading to assess the validity of questionnaire measures against a single determination of an atmospheric or biologic marker. We suggest that atmospheric and biologic markers offer complementary approaches to questionnaires for assessment of exposure to environmental tobacco smoke, and that these methods should be used together to estimate the magnitude of misclassification from questionnaire responses.

Acknowledgment

The writers thank Dr. Helen Van Vunakis for providing the reagents for the radioimmunoassay, and Irene Walkiw for technical assistance in performing the assays.

References

1. U.S. Department of Health and Human Services. The health consequences of involuntary smoking, a report of the Surgeon General. Rockville, MD: U.S. Department of Health and Human Services, 1986. (DHHS publication no. [CDC] 87-8398).
2. National Research Council. Environmental tobacco smoke. Measuring exposures and assessing health effects. Washington, DC: National Academy Press, 1986.
3. Coultas DB, Peake GT, Samet JM. Questionnaire assessment of lifetime and recent exposure to environmental tobacco smoke. Am J Epidemiol 1989; 130:338-47.
4. Langone JJ, Gjika HB, Van Vunakis H. Nicotine and its metabolites. Radioimmunoassays for nicotine and cotinine. Biochemistry 1973; 12: 5025-30.
5. Faulkner WR, King JW. Renal function. In: Tietz NW, ed. Fundamentals of clinical chemistry. Philadelphia: W. B. Saunders, Co., 1976; 975-1014.
6. Turner WA, Marple VA, Spengler JD. Indoor aerosol impactor. In: Liu BYH, Pui D, Fissan H, eds. Aerosols. New York: Elsevier Science Publishing Co., 1984; 527.
7. Hammond SK, Leaderer BP, Roche AC, Schenker M. Collection and analysis of nicotine as a marker for environmental tobacco smoke. Atmos Environ 1987; 21:457-62.
8. SAS Institute, Inc. SAS user's guide: Statistics. 5th ed. Cary, NC: SAS Institute, Inc., 1985.
9. Friedman GD, Petitti DB, Bawol RD. Prevalence and correlates of passive smoking. Am J Public Health 1983; 73:401-5.
10. Spengler JD, Dockery DW, Turner WA, Wolfson JM, Ferris BG Jr. Long-term measurements of respirable sulfates and particles inside and outside homes. Atmos Environ 1981; 15:23-30.
11. Brunekreef B, Boleij JSM. Long-term average suspended particulate concentrations in smokers' homes. Int Arch Occup Environ Health 1982; 50:299-302.
12. Muramatsu M, Umemura S, Okada T, Tomita H. Estimation of personal exposure to tobacco smoke with a newly developed nicotine personal monitor. Environ Res 1984; 35:218-27.
13. Henderson FW, Reid HF, Morris R, *et al.* Home air nicotine levels and urinary cotinine excretion in preschool children. Am Rev Respir Dis 1989; 140:197-201.
14. Coultas DB, Howard CA, Peake GT, Skipper BJ, Samet JM. Salivary cotinine levels and involuntary tobacco smoke exposure in children and adults in New Mexico. Am Rev Respir Dis 1987; 136:305-9.